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RESEARCH MEMORANDUM

SPONTANEOUS IGNITION OF PENTABORANE SPRAYS IN A HOT-AIR STREAM

By Erwin A. Lezberg and Albert M. Lord

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

SPONTANEOUS IGNITION OF PENTABORANE SPRAYS IN A HOT-AIR STREAM

By Erwin A. Lezberg and Albert M. Lord

SUMMARY

The boron hydrides, because of their high reactivity, have been suggested for use as ignition or relight fuels in jet engines. Spontaneous-ignition temperatures and ignition delays were therefore determined for pentaborane in a heated-air stream.

Ignition temperatures from 600° to 675° F were found for ignition delays of about 3 to 20 milliseconds over a range of pressure from 5 to 29 inches of mercury absolute. The effect of temperature on ignition delay can be represented by the Arrhennius equation. The effect of pressure on ignition temperature can be represented by an equation of the type

$$p^n = ke^{-\frac{E}{RT}}$$

where p is absolute pressure, n and k are constants, E is the activation energy, R is the universal gas constant, and T is the absolute temperature. The mean value of n was 1.6 for combustor pressures of 10 to 29 inches mercury absolute.

A flame stabilizer reduced ignition temperatures for pentaborane.

INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to determine the performance of boron hydride fuels in jet-engine combustor systems. The high reactivity of these fuels makes them potentially useful as ignition or relight fuels. In addition, under some operating conditions, no flameholder will be required with these fuels. An investigation was therefore made to determine the conditions under which pentaborane will ignite spontaneously.

Small concentrations of decaborane in gasoline substantially reduce the ignition temperature below that for gasoline (ref. 1). Reference 2 shows that pentaborane-air mixtures are spontaneously inflammable over a

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wide range of composition. Unpublished data for work done at the Lewis laboratory show that the lean limit for pentaborane-air mixtures is 14 percent by volume at a pressure of 1 atmosphere and about 55 percent by volume at 0.1 atmosphere. Other work has been done at this laboratory on the spontaneous ignition of pentaborane in air in a $1\frac{7}{8}$-inch-diameter ram-jet combustor at elevated air temperatures. Spontaneous ignition seemed governed principally by temperature. Ignition temperature was influenced by burner length and configuration. No influence of combustor velocity or equivalence ratio was found over the range investigated. 3746

The specific objective of this study was to determine the limits of temperature, pressure, and ignition delay for spontaneous ignition of pentaborane in a flow system that provided fuel residence times comparable to those for a jet-engine combustor.

Ignition temperatures were determined for pentaborane in a 6-inch-diameter duct for a range of delay time from 3 to 20 milliseconds and of pressure from 5 to 29 inches of mercury absolute. The data were correlated by semiempirical equations. The effect of a 3/4-inch-diameter rod flameholder on the ignition temperatures was also determined.

Some spontaneous-ignition data were obtained with amyl nitrate in this apparatus for comparison with the results of reference 3.

APPARATUS

The spontaneous-ignition test setup is shown in figure 1. The main air supply could be heated to 700° F in the heat exchanger. Higher temperatures were reached by burning part of the combustion air in a turbojet can combustor. The test section, a 6-inch pipe 41 inches long, had $\frac{3}{4}$-inch-pipe taps at $4\frac{1}{2}$-inch intervals for installing the fuel injector, a $\frac{3}{4}$-inch rod flameholder, and a sampling probe. At the downstream end of the test section, an air-atomized water spray quenched the fuel-air mixture.

The fuel injector, which was fabricated from brass and contoured to an airfoil shape, contained passages for cooling water, atomizing air, and fuel. The injector and water quench are shown in figure 2.

Fuel System

The test and JP fuels were piped to the injector from separate tanks. Both were maintained at the same pressure by pressurization with helium from the same source. The test fuel passed, in order, through a solenoid valve, a filter, sight glass, and a spring-loaded check valve that opened when the pressure difference exceeded 8 pounds per square inch to a junction with the JP-fuel line. The JP fuel passed through a solenoid valve; a check valve that opened at a pressure of less than 2 pounds per square inch; and a remote indicating, rotating-vane flowmeter to the fuel injector. Most of the fuel pressure drop occurred across the injector orifice.

When both solenoid valves were opened, only the JP fuel flowed. A timing device then closed the JP-fuel valve for 3/4 second, permitting the test fuel to flow and fill from 2 to 4 feet of the line to the fuel injector. The slug of test fuel was preceded and followed by the JP fuel and entered the combustor at the volume flow rate indicated by the JP-fuel flowmeter.

The injector fuel passage was thus cooled before the test fuel entered and was flushed clean after the test fuel passed. Both cooling and flushing are necessary because pentaborane decomposes rapidly with time to a solid residue at the temperature of the air stream.

Instrumentation

Combustion air flow was measured upstream of the heat exchanger by a standard orifice.

Inlet-air temperature was taken $4\frac{1}{2}$ inches upstream of the fuel injector by a chromel-alumel thermocouple at 0.707 radius from the center of the duct.

A strain-gage pressure pickup was used to determine ignition and is shown in section B-B of figure 1. The pressure pickup was connected to one channel of a two-channel strip recorder. Fuel flow rate was determined by a rotating-vane flowmeter, whose output was recorded on the second channel of the recorder.

Atomizing-air flow for the fuel injector was metered through a calibrated rotameter.

Surveys were made of fuel and temperature distribution across the duct; the apparatus and techniques for the surveys are described in appendix A. Measurements of turbulence intensity and scale were made with a constant-temperature hot-wire anemometer. The methods and equipment used are discussed in appendix B.

TEST PROCEDURE

Ignition delay τ of the fuel-air mixture was determined by

$$\tau = \frac{l}{U} \tag{1}$$

where l is the distance between the fuel injector and water quench spray, and U the mean velocity of the air stream.

At a constant duct pressure and air flow, the test fuel was injected and the pressure record examined for an indication of ignition. The temperature was then raised if there had been no ignition or lowered if there was ignition, until the threshold ignition temperature was determined.

Under some conditions, after several consecutive ignitions, ignition temperatures as much as a hundred degrees lower than expected would result. This was caused by deposit buildup on the fuel injector. The problem was eliminated by washing the injector at intervals with a stream of water.

Spontaneous-ignition temperatures for pentaborane were determined over the following range of conditions:

τ 3 to 20 milliseconds

l 27 and 36 inches

p 5, 10, 15, 20, and 29 inches of mercury absolute

RESULTS AND DISCUSSION

Evaluation of Experimental Method

Determination of ignition delays for different duct lengths. - Tests were conducted with distances between the fuel injector and the water quench of 27 and 36 inches in order to determine whether length alone influences ignition temperature. For the range of conditions covered in this investigation, ignition temperatures for equal values of ignition delay τ were the same for both duct lengths.

Fuel-air ratio and temperature surveys in the test section. - Surveys of the fuel-air-ratio distribution were taken at the same conditions as the ignition data for the extremes of velocity encountered at a duct pressure of 29 inches of mercury. These surveys are shown in figure 3. The peak fuel concentration at the 27.8-inch sampling distance was above the range of the fuel-air analyzer and hence is not plotted. The temperature drop presented was due to evaporation and heating of the fuel. The temperature scale has been adjusted so that the temperature resulting from complete evaporation and the corresponding fuel-air ratio have common ordinates.

The data of figure 3 indicate that the desired conditions were obtained in the apparatus; that is, a core of high fuel concentration existed throughout most of the duct and low fuel concentrations in the low-velocity region near the duct walls.

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<u>Effect of fuel-air ratio</u>. - The effect of varying fuel-air ratio on the ignition temperature of pentaborane for constant ignition delay is shown in figure 4. At the lower fuel-air ratios, a marked increase in ignition temperature occurred; as the fuel concentration was increased, however, the ignition temperature reached a minimum and became independent of fuel-air ratio. With the exception of the data of figure 4, where fuel-air ratio varies, the ignition data were taken for a constant fuel-air ratio of 0.0135 ±0.0005.

The amount of air for atomizing the fuel was held constant rather than a fixed percentage of the fuel-flow rate, and this may have resulted in poor sprays at the higher fuel-flow rates.

<u>Turbulence intensity and velocity surveys</u>. - A fuel injector contoured to airfoil shape was used to minimize the effect of the injector on turbulent mixing of the fuel and air. Surveys of the turbulence intensity $\sqrt{\overline{u^2}}/U$ and velocity U were taken at various stations downstream of the injector and are shown in figure 5. (The quantity $\sqrt{\overline{u^2}}$ is the root mean square of the turbulent velocity fluctuations in the direction of the stream velocity U.) The extremes of velocity from the profile represent a ±10 percent deviation from the mean in the region where substantial concentrations of fuel are present. This presumably could result in a like error in the values presented for ignition delay time.

The method of sampling the mixture for the fuel-air profiles gave time average values of fuel concentration that do not reveal the heterogeneity that probably resulted from atomized spray being injected into a turbulent air stream. Mixing was not expected to be complete, and zones of rich mixture probably persisted throughout the reaction zone. The nature of the distribution pattern of incompletely diffused fuel filaments in a turbulent stream is suggested in reference 4, which states that although average-temperature profiles in the wake of a heated wire gave the expected Gaussian distribution, instantaneous measurements showed that pulses representing peak temperatures were obtained. Reference 4 attributes these pulses to the displacement of the fluid sheet by the turbulence eddies, diffusion within the sheet taking place by molecular diffusion only. This condition can occur if the scale of the turbulence is large compared with the size of the source. This was found to be the case in the present investigation (appendix B); therefore, the observations of reference 4 might be applicable here.

Effect of Pressure and Temperature on Pentaborane Ignition

The ignition data are shown in figure 6 as a plot of temperature against ignition delay for lines of constant pressure. Only one ignition point is shown for a duct pressure of 5 inches of mercury absolute. Scatter for the pressure of 10 inches of mercury absolute resulted mostly from low fuel flows, which brought the data into the region where ignition temperature was strongly dependent on fuel-flow rate (fig. 4).

The dashed curve in figure 6 is based on minimum temperatures found by extrapolating the appropriate curves of figure 4. 3746

Temperature effect on ignition delay. - The data of figure 6 are replotted in figure 7 as the logarithm of ignition delay against the reciprocal of absolute temperature. Over the range of temperatures investigated, the results are consistent with the Arrhennius relation

$$\frac{1}{\tau} = Ae^{-\frac{E}{RT}} \qquad (2)$$

where A is a constant.

Plotting $\log \tau$ against $1/T$ makes the slope of the lines equal to $E/2.303\ R$. In this way, apparent activation energies for each of the constant-pressure lines were determined and are presented in the following table:

Duct pressure, p, in. Hg abs	Apparent activation energy, E, kcal/mol
10	21.8
15	26.9
20	28.1
29	31.6

Pressure effect on ignition. - The pentaborane results indicate that there is an inverse pressure dependence on ignition which is contrary to that generally encountered for hydrocarbon ignition. This behavior is characteristic of a chain-reaction mechanism in which chain branching and chain breaking compete, for example, the hydrogen-oxygen reaction (ref. 5, p.292).

Reactions of this type exhibit upper and lower pressure limits for ignition. The lower limit is a function of the apparatus and is probably due to chain breaking at the wall. The upper limit is independent of the apparatus and is believed due to a gas-phase chain-breaking reaction which is favored by increasing pressure (ref. 5, p. 264).

If the chain-branching reaction is a lower-order function of pressure than the breaking reaction, a pressure limit will be reached above which explosion cannot occur. With the branching assumed to be an exponential function of temperature, the condition at the upper explosion limit, where branching and breaking rates are equal, is given by

$$k\ p^n = e^{-\frac{E}{RT}} \tag{3}$$

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Written in logarithm form, equation (3) is

$$\ln p = \frac{-E}{nRT} + k' \tag{4}$$

Upper and lower ignition limits for diborane have been studied (refs. 6 and 7), and a chain-branching mechanism proposed.

These limit curves were determined in static systems and represent minimum ignition temperatures. For higher temperatures, a family of such curves might exist for fixed ignition delays.

An inverse pressure effect on ignition delay has been found in a flow system for carbon monoxide and hydrogen (ref. 8), where increased delays with increasing pressure were observed in some regions.

A cross plot of the ignition data from figure 6 is shown in figure 8. The curves are a plot of equation (4) for delay times of 5, 8, and 12 milliseconds.

The slope of these lines is equal to $-E/2.303\ nR$, and the pressure exponent n can be determined from the activation energy.

A further correlation is shown in figure 9 as a plot of τp^n against $1/T$. The ignition data can be represented by a single line when n is taken as -1.6.

Effect of Flameholder on Ignition Temperature

Since the spontaneous-ignition temperatures found for pentaborane were higher than inlet temperatures for many operating conditions of jet-engine combustors, it was of interest to determine the effectiveness of a flameholder in reducing the ignition temperature.

Ignition temperatures were determined at two values of ignition delay at a duct pressure of 20 inches of mercury absolute with a $\frac{3}{4}$-inch-diameter rod placed $4\frac{1}{2}$ inches downstream of, and in the same plane with, the fuel injector. The results are shown in figure 10 together with the curve for no flameholder from figure 6. The 20° to 35° F drop in ignition temperature due to the rod corresponds to a large increase in residence time. Presumably, the ignition occurs in a portion of the fuel-air mixture that has encountered an increased residence time because the mixture has passed through the recirculation zone in the wake of the rod. The change in ignition temperature with ignition delay indicates that ignition is still occurring immediately upstream of the quench and propagating upstream. After ignition, the flame stabilized on the rod, whereas without the flameholder, stabilization occurred at the fuel injector. 3746

With a flameholder that blocked a large percentage of the duct area, ignition could possibly always take place in the recirculation zone since some fuel would remain in this zone for relatively long periods.

Ignition of Amyl Nitrate

For purposes of comparison of the results of this investigation with those of reference 3, some spontaneous-ignition temperatures were determined with amyl nitrate. This material was readily available and its ignition could be accomplished within the temperature limitations of the apparatus.

Ignition temperatures were determined for amyl nitrate at a pressure of 29 inches of mercury absolute and an ignition delay of 24 milliseconds ±20 percent for a range of fuel-air ratios. The results are shown in figure 11. A large effect of fuel concentration on ignition temperature is apparent. The percentage of atomizing air was varied almost twofold for a constant fuel-air ratio without any significant effect on ignition temperature. Reference 3 reports ignition temperatures of 950° and 990° F for ignition delays of 28 and 19 milliseconds.

The data of figure 11 were corrected to a mean value of 24.2 milliseconds by use of the results shown in reference 3 and are shown by the dashed line. For the over-all very lean mixtures of reference 3, the results appear comparable.

SUMMARY OF RESULTS

An investigation of the spontaneous ignition of pentaborane gave the following results:

1. Pentaborane sprays ignited spontaneously over a range of pressures of 5 to 29 inches of mercury, ignition delays of 3 to 20 milliseconds and inlet-air temperatures of 600° to 675° F.

2. The apparent activation energy for the ignition of pentaborane in air increased from 21.8 to 31.6 kilocalories per mole as the pressure increased from 10 to 29 inches of mercury.

3. At constant ignition delay, the ignition temperature varied approximately as the pressure to the -1.6 power.

4. A flame stabilizer reduced the spontaneous-ignition temperature.

3746 5. The spontaneous-ignition temperature of amyl nitrate at 29 inches of mercury and an ignition delay of 24 milliseconds varied from 1060° to 640° F as the fuel-air ratio was varied from 0.020 to 0.052.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 1, 1955

APPENDIX A

FUEL-AIR-RATIO AND TEMPERATURE PROFILES IN THE TEST SECTION

Surveys of fuel and temperature distribution were made at test conditions bracketing those for the ignition data. Acetone was used for these surveys because its physical properties are similar to those of pentaborane. Temperature surveys were taken with a thermocouple that was fastened near the opening of the sampling probe so that data for fuel concentration and temperature drop due to fuel evaporation and heating were taken simultaneously. The probe was installed at the desired axial position and moved radially for the surveys. Gas samples were withdrawn at stream velocity and passed through a fuel-air analyser which is described in reference 9.

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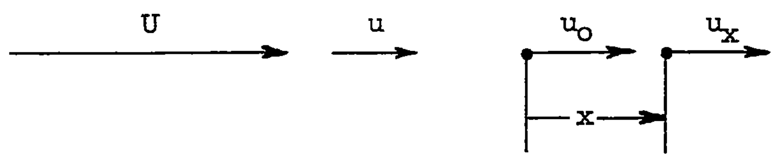
APPENDIX B

TURBULENCE MEASUREMENTS

As shown in reference 10, the turbulence parameters of interest in mixing are the turbulence intensity, the root-mean-square value of the turbulent velocity fluctuations, and the correlation coefficient, which is a statistical value expressing the relation between fluctuating velocities at two different points in the stream. Measurements of the turbulence intensity $\sqrt{\overline{u^2}}$ and the correlation coefficient f were convenient and were made with constant-temperature anemometry equipment partially described in reference 11. Additional equipment necessary for the measurement of the correlation coefficient f has been designed at the Lewis laboratory on principles described in reference 12.

The turbulence intensity measurements are shown in figure 5(b) and the correlation-coefficient measurements are shown in figure 12. The turbulence intensity $\sqrt{\overline{u^2}}$ and correlation coefficient f are described by the following diagram:



where u_o and u_x represent values of the velocity fluctuations at two points in the stream separated by the distance x. Thus, the correlation coefficient is expressed by

$$f = \frac{\overline{u_o u_x}}{\overline{u^2}}$$

The scale of turbulence L, a measure of the mean size of the turbulent eddies, was calculated from the correlation-coefficient data with the relation (ref. 12)

$$L = \int_0^\infty f dx$$

and was found to be 0.112 foot. The turbulence microscale λ, which represents the mean size of the smallest eddies, was also calculated from the correlation-coefficient data using the relation (ref. 13)

$$\lambda = \left(\frac{x^2}{1 - f}\right)^{1/2}$$

and was found to be 0.025 foot.

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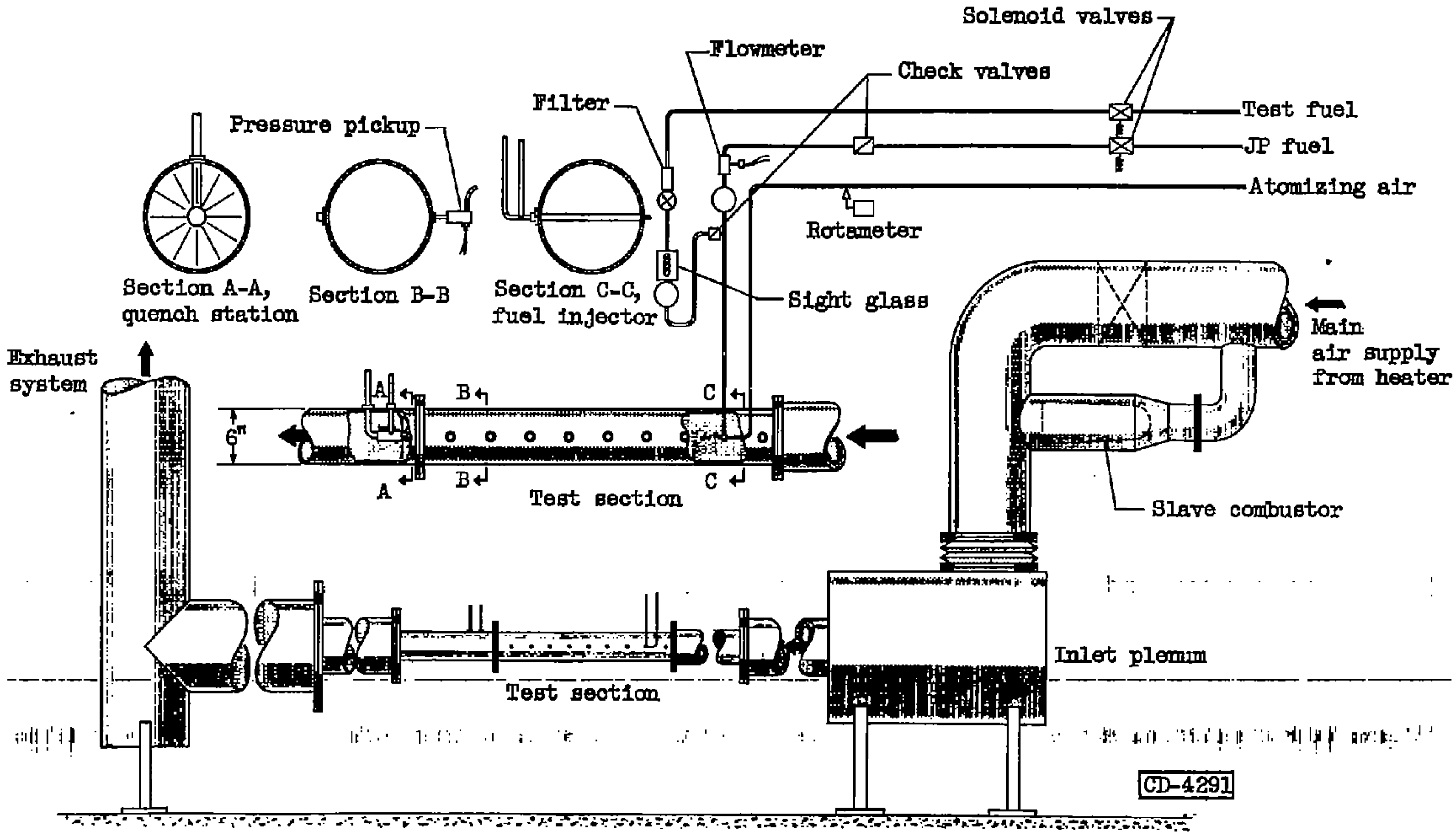

Figure 1. - Spontaneous-ignition test setup.

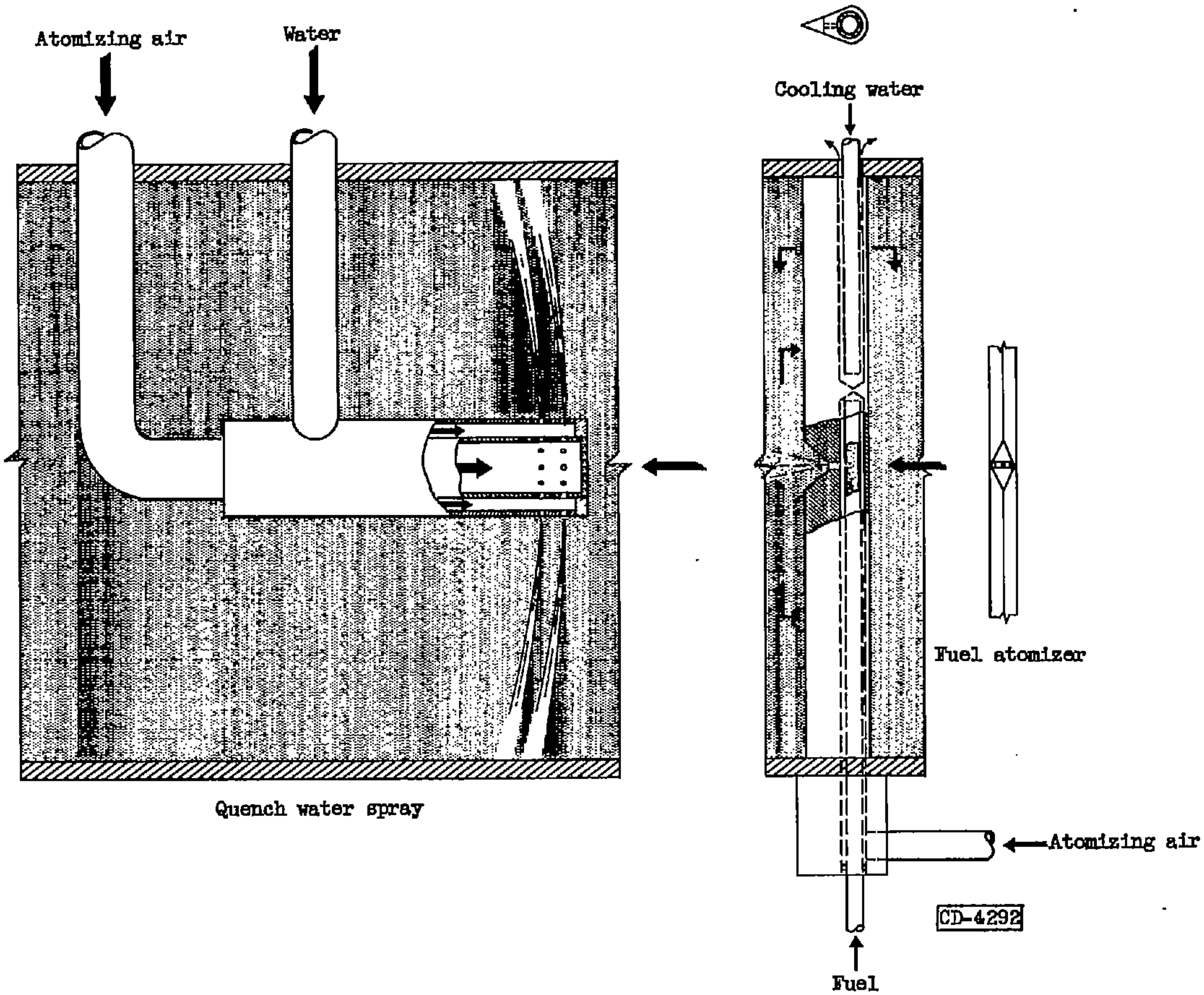

Figure 2. - Details of water quench and fuel atomizers.

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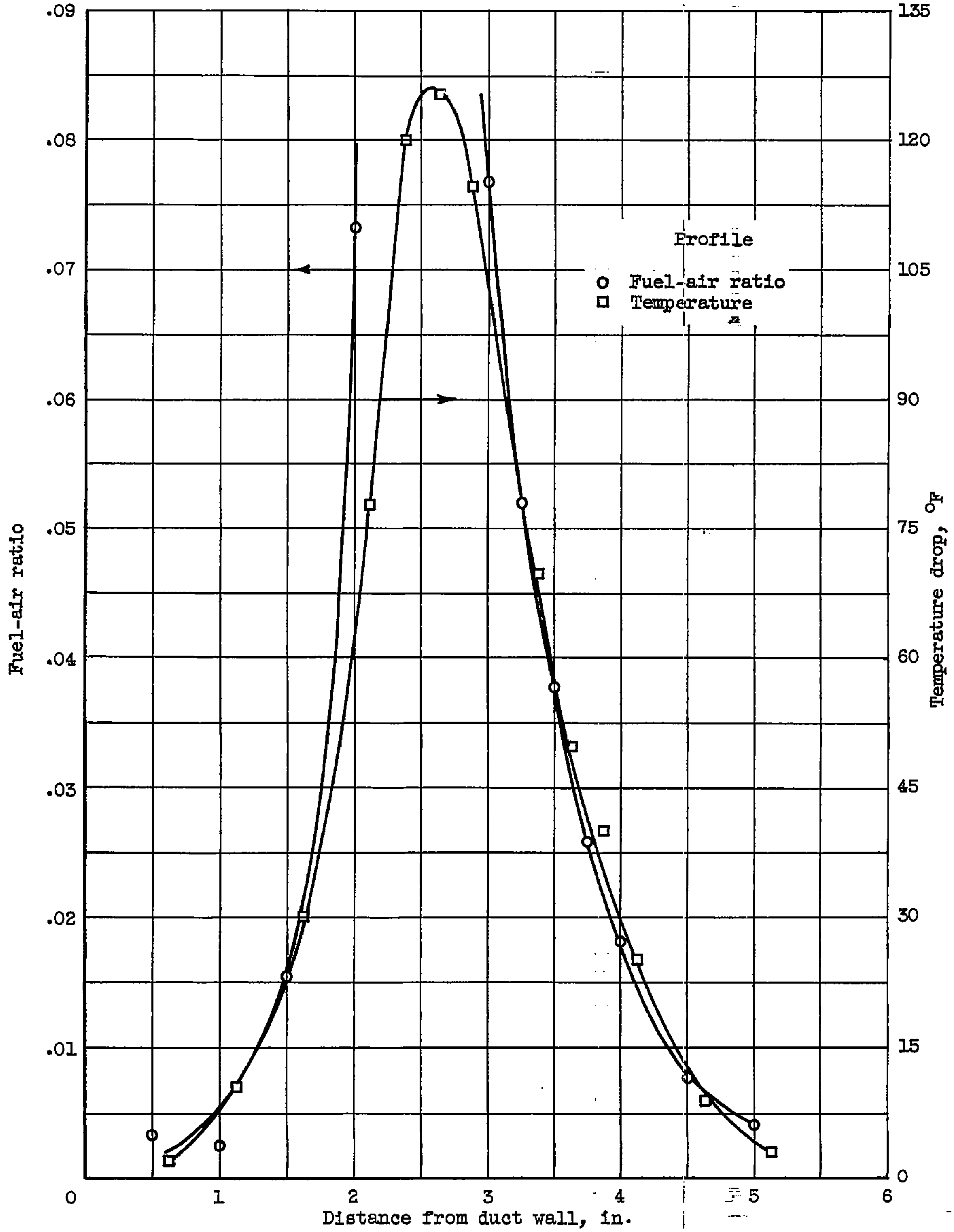
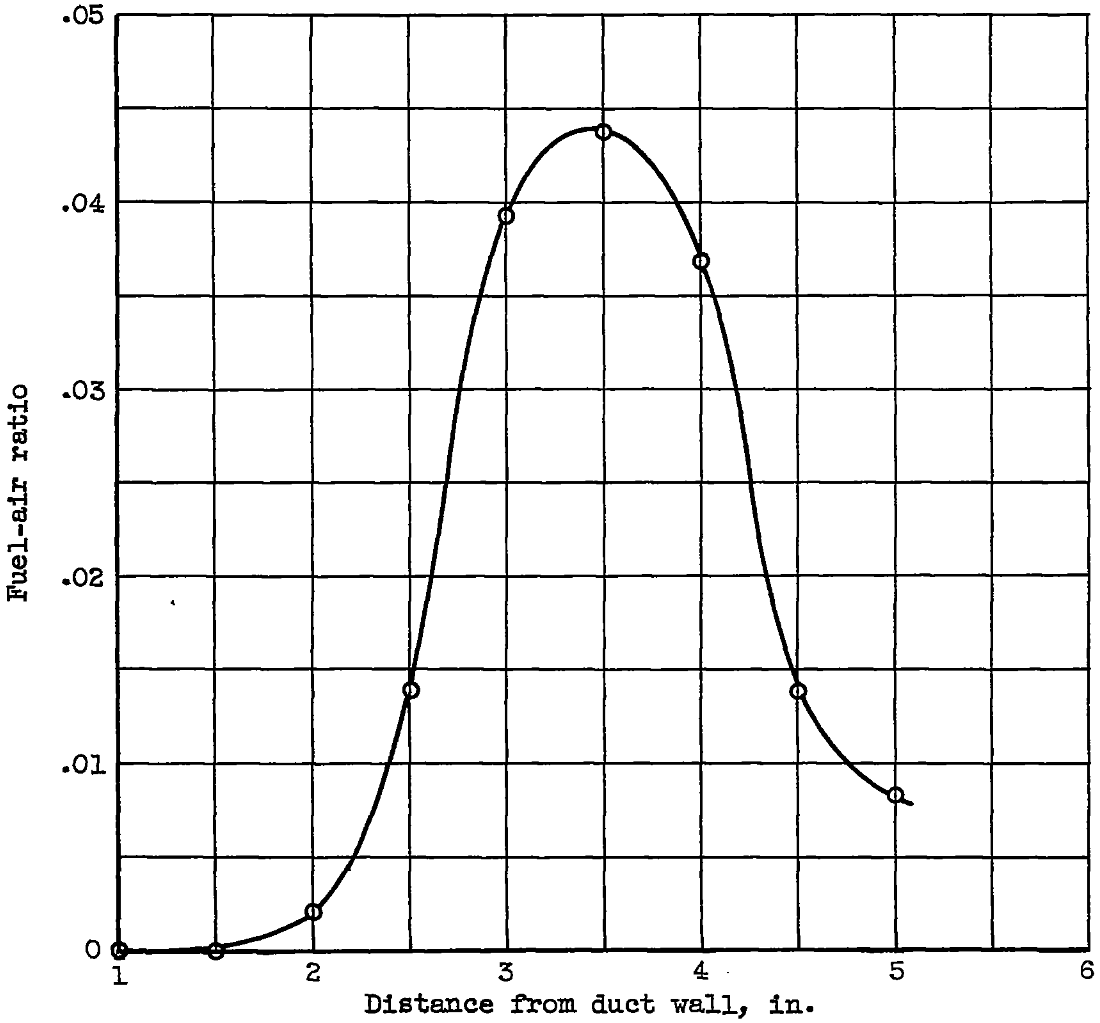


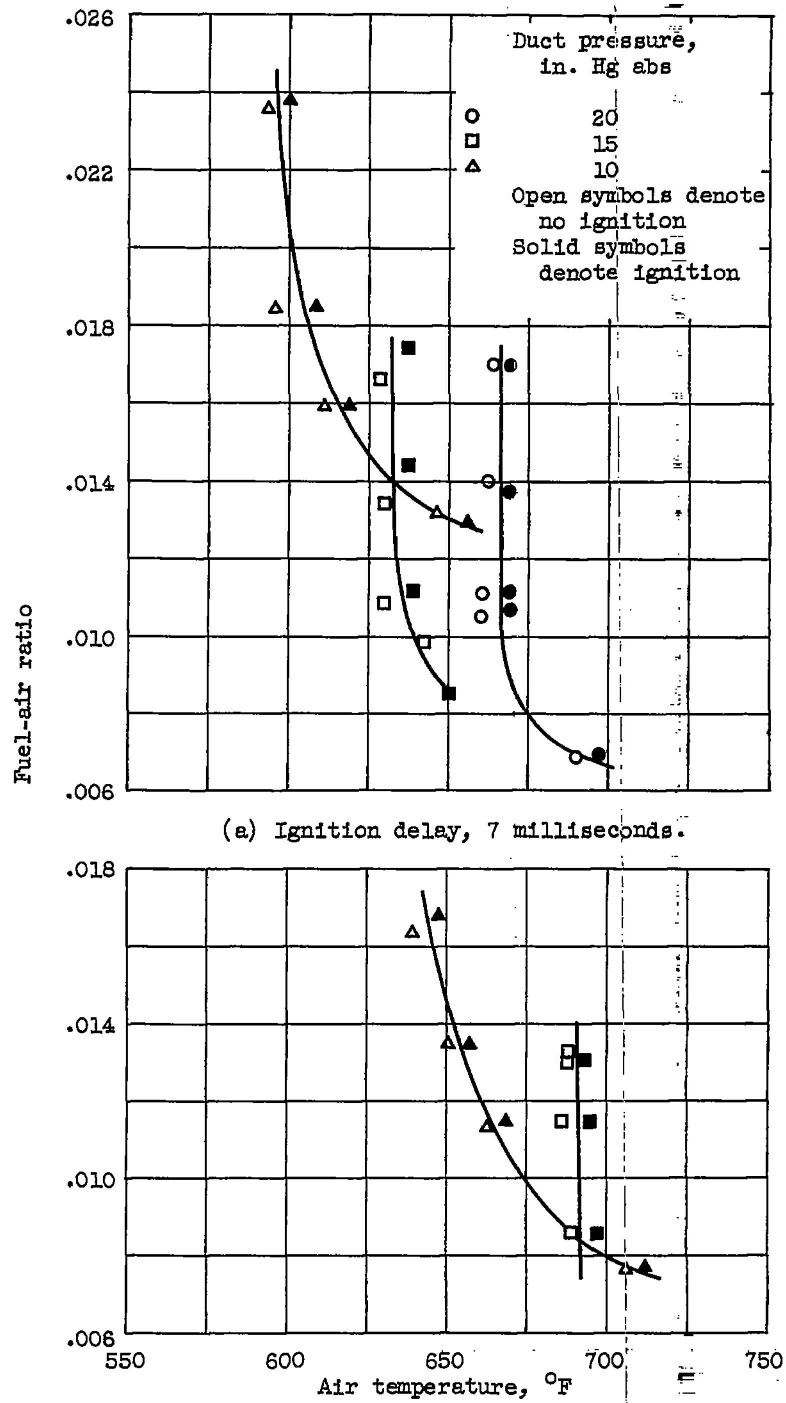
(a) Distance between fuel injector and water sampling probe, 24.8 inches; mean velocity of air stream, 260 feet per second.

Figure 3. - Fuel-air-ratio and temperature profiles for 6-inch-diameter duct. Pressure, 29 inches of mercury absolute; air temperature, 600° F.



(b) Distance between fuel injector and water sampling probe, 33.8 inches; mean velocity of air stream, 130 feet per second.

Figure 3. - Concluded. Fuel-air-ratio and temperature profiles for 6-inch-diameter duct. Pressure, 29 inches of mercury absolute; air temperature, 600° F.



(b) Ignition delay, 4 milliseconds.

Figure 4. - Effect of over-all fuel-air ratio on ignition temperature of pentaborane at constant ignition delay.

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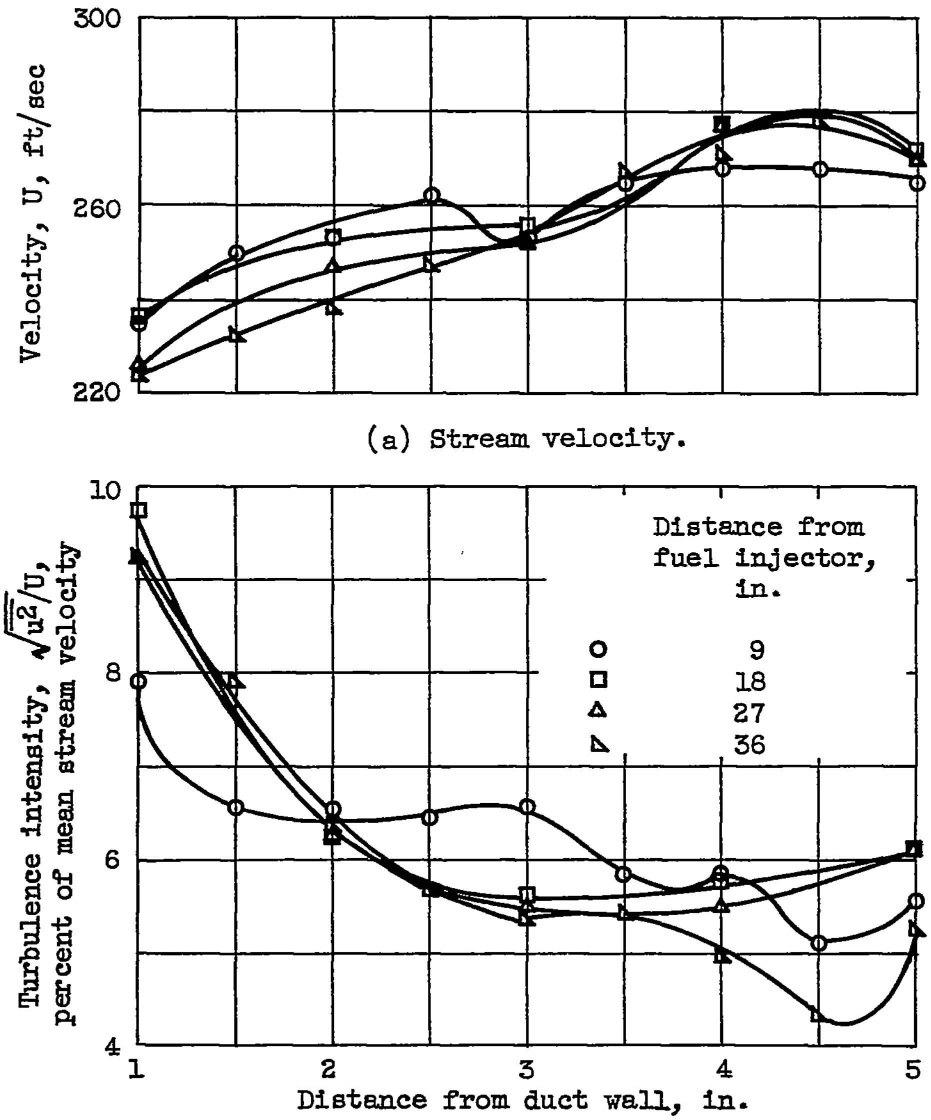

(a) Stream velocity.

(b) Axial turbulence intensity.

Figure 5. - Velocity and turbulence-intensity profiles at various stations in 6-inch duct. Pressure, 29 inches of mercury absolute; air temperature, 200° F.

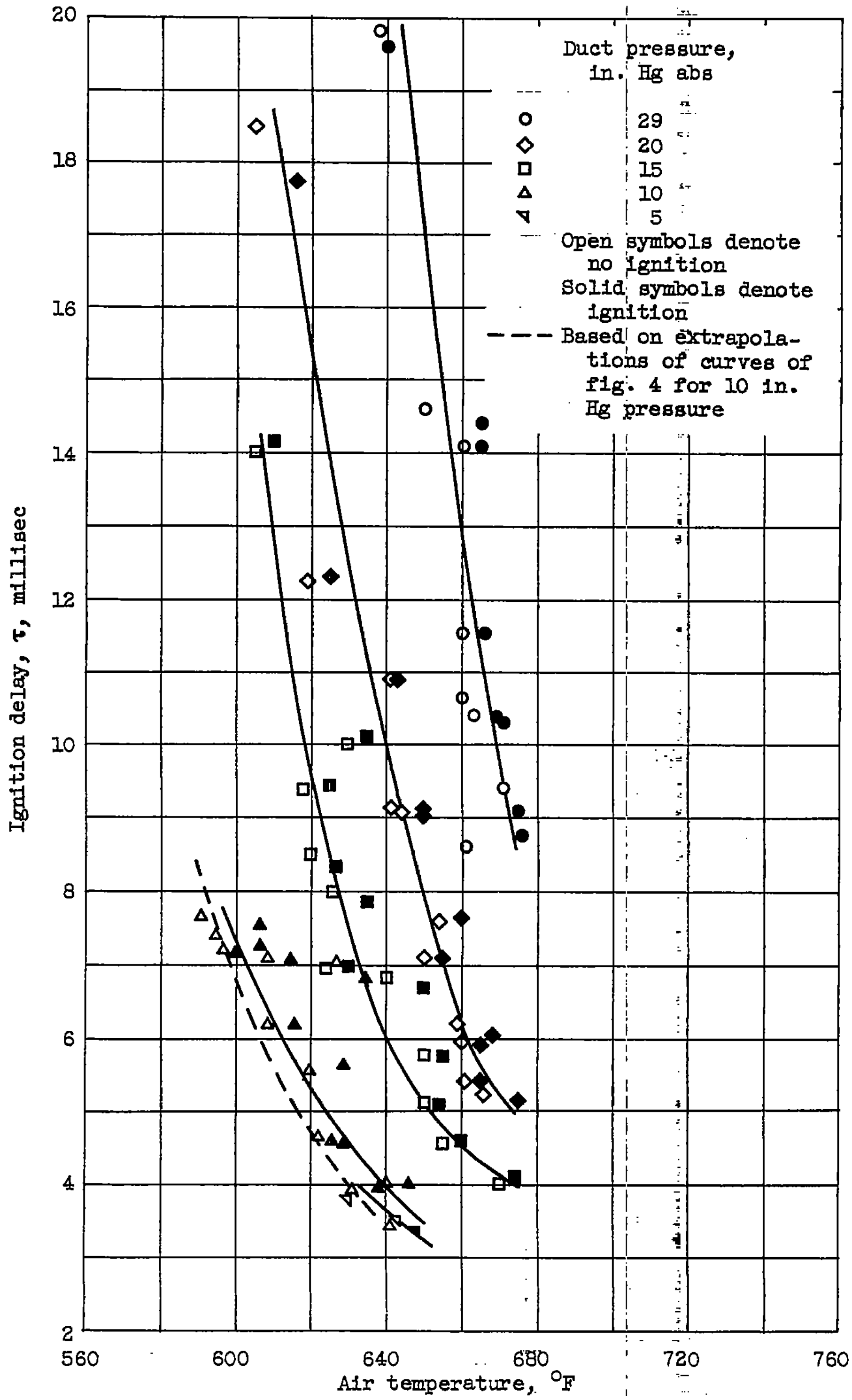

Figure 6. - Effect of temperature and pressure on ignition delay of pentaborane.

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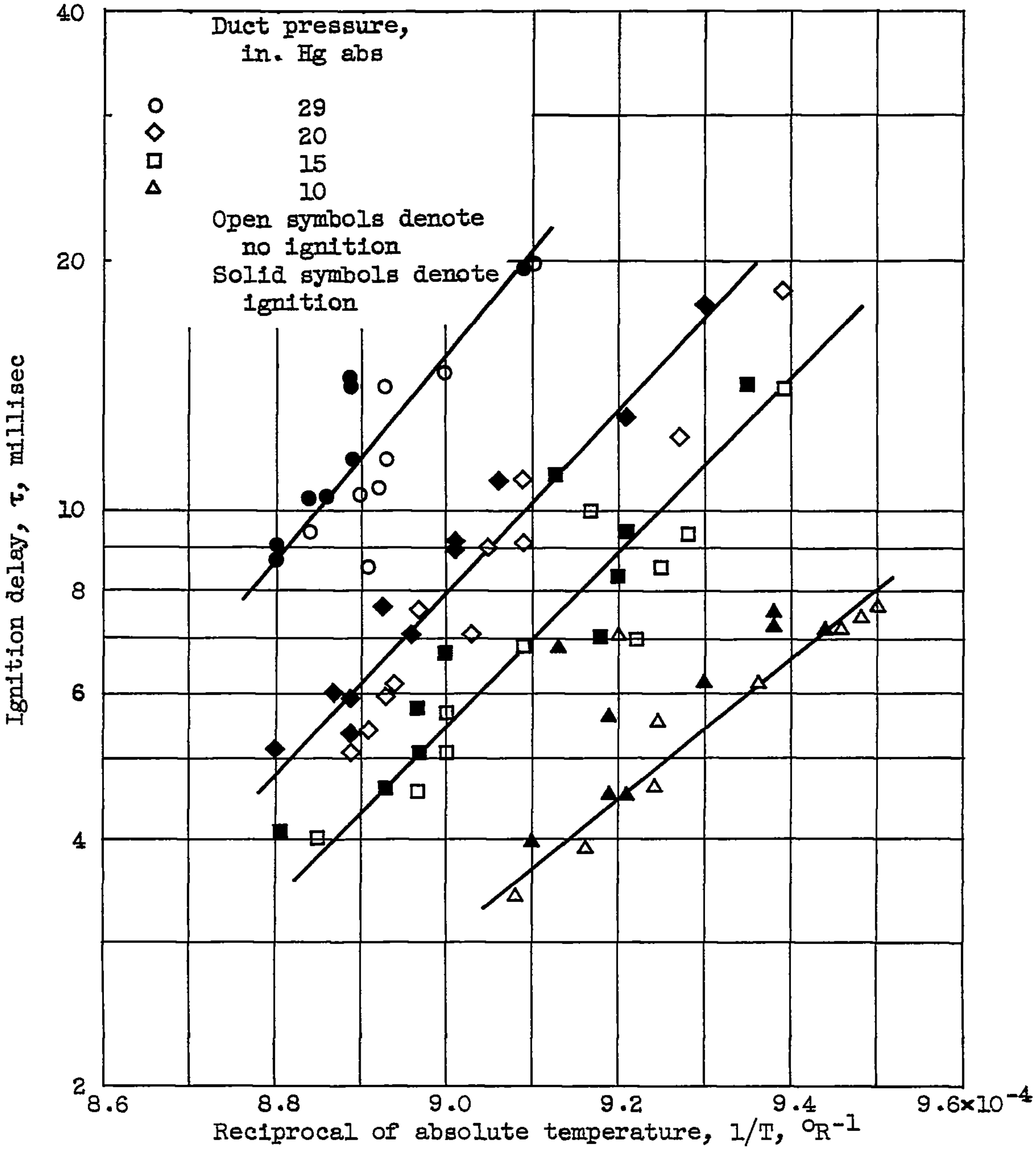

Figure 7. - Effect of temperature and pressure on ignition delay of pentaborane.

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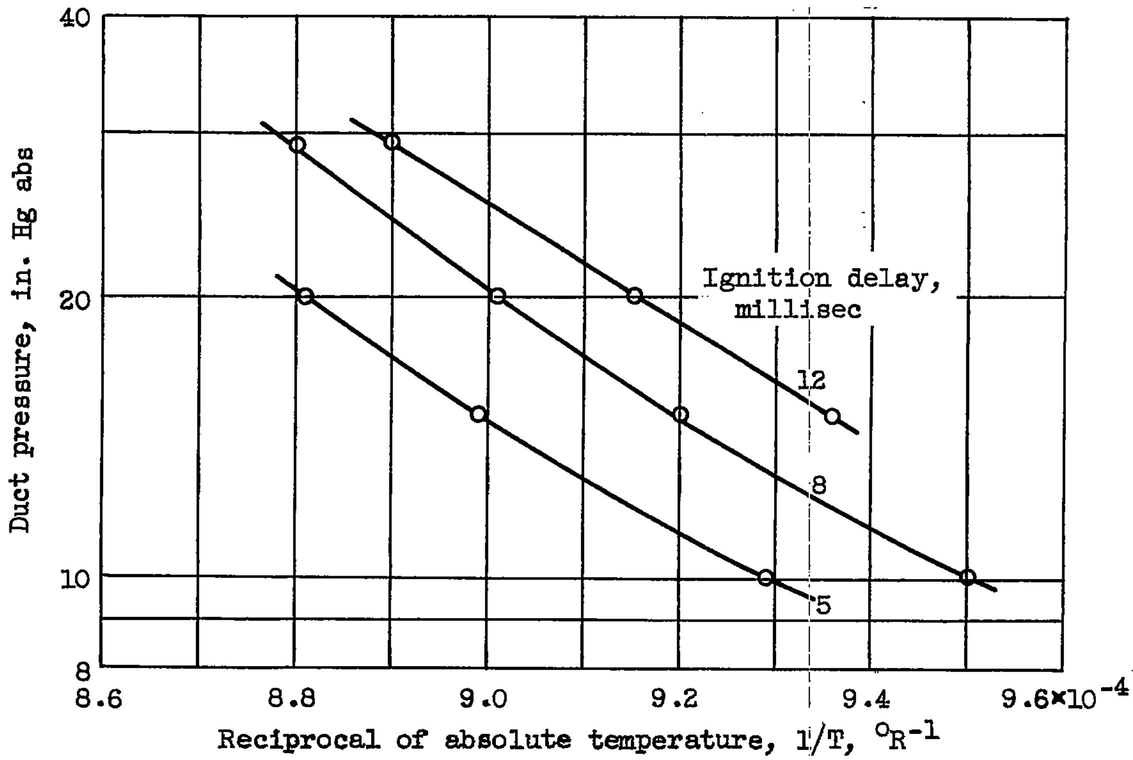

Figure 8. - Variation of log of absolute pressure with reciprocal of absolute temperature at constant ignition delay.

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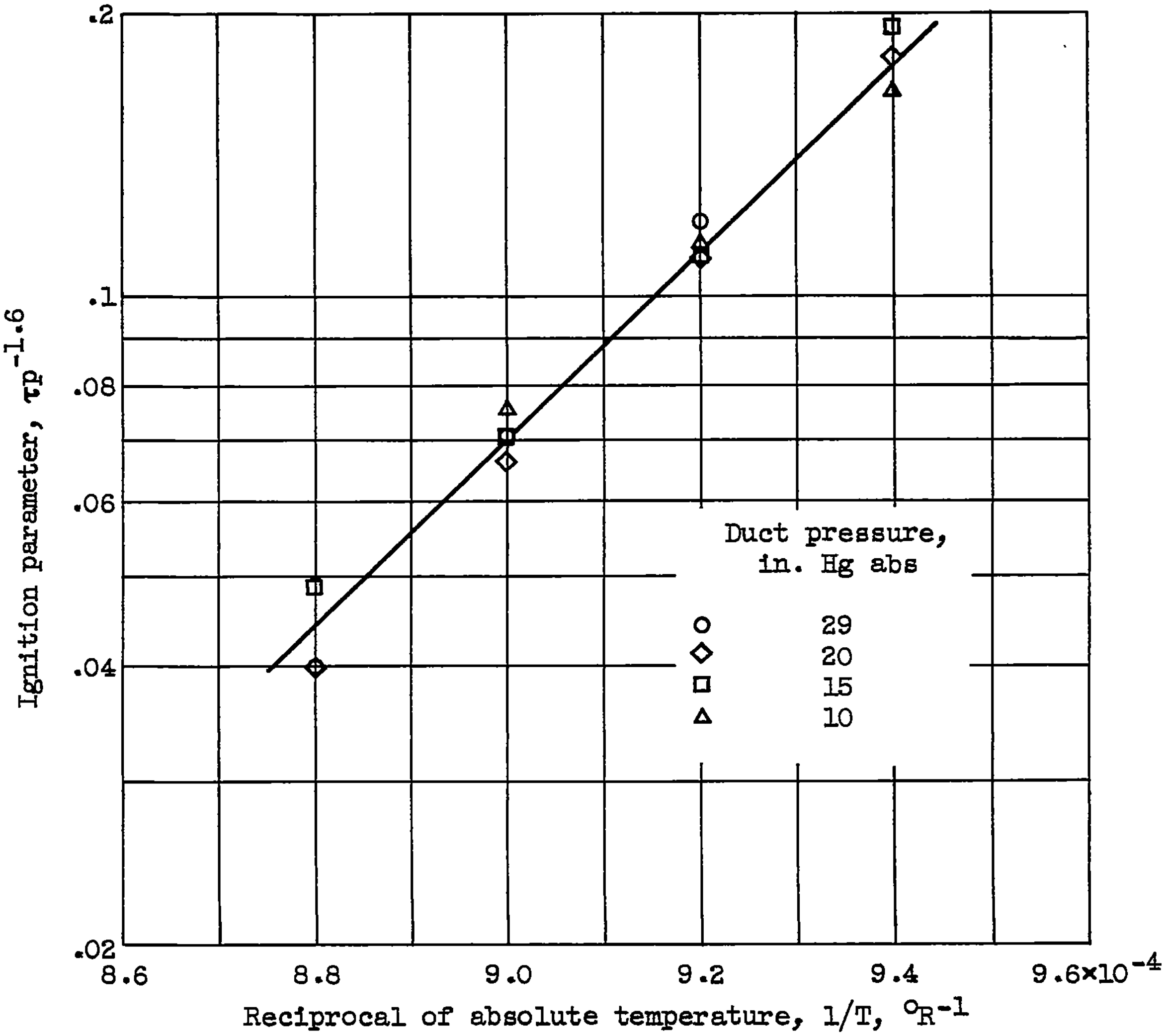

Figure 9. - Correlation of ignition data for pentaborane.

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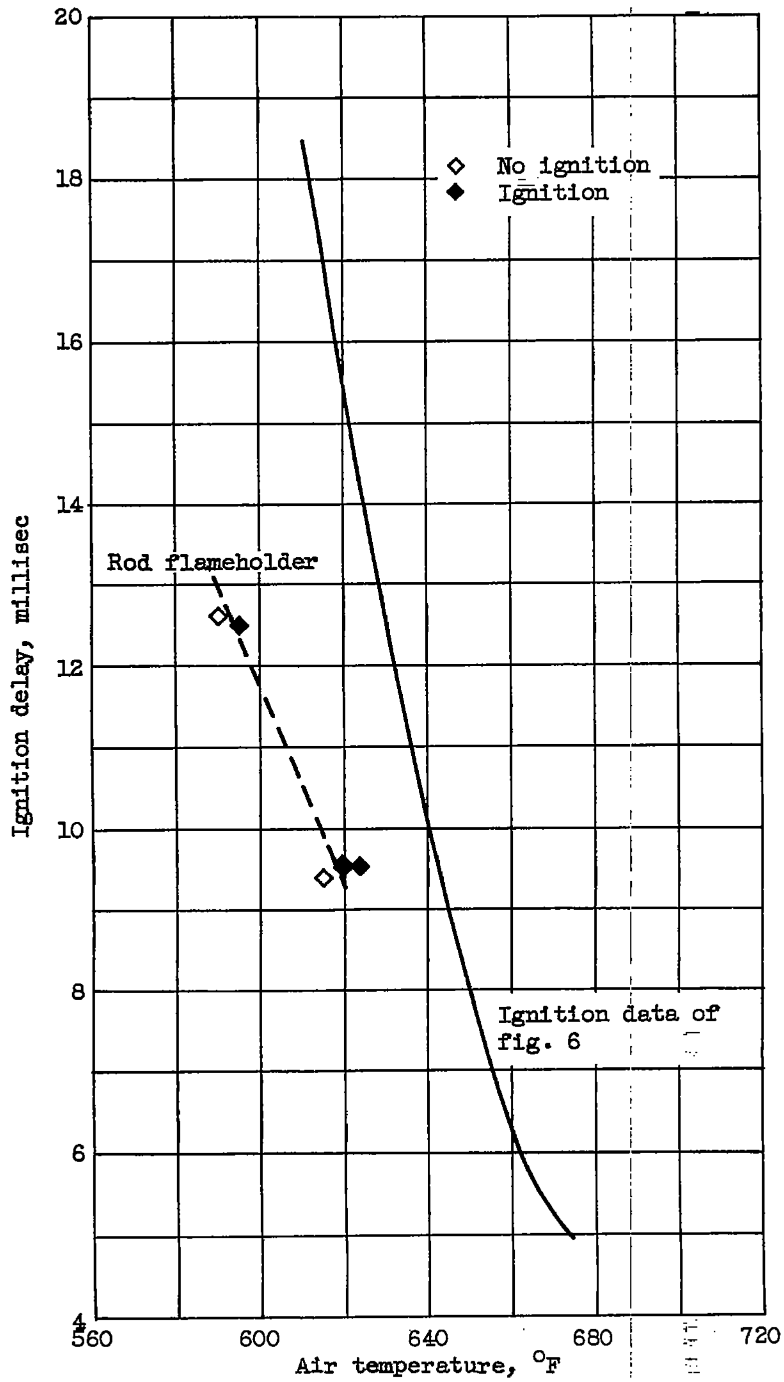

Figure 10. - Effect on ignition temperature of 3/4-inch-diameter rod located $4\frac{1}{2}$ inches downstream of fuel injector. Pressure, 20 inches of mercury absolute.

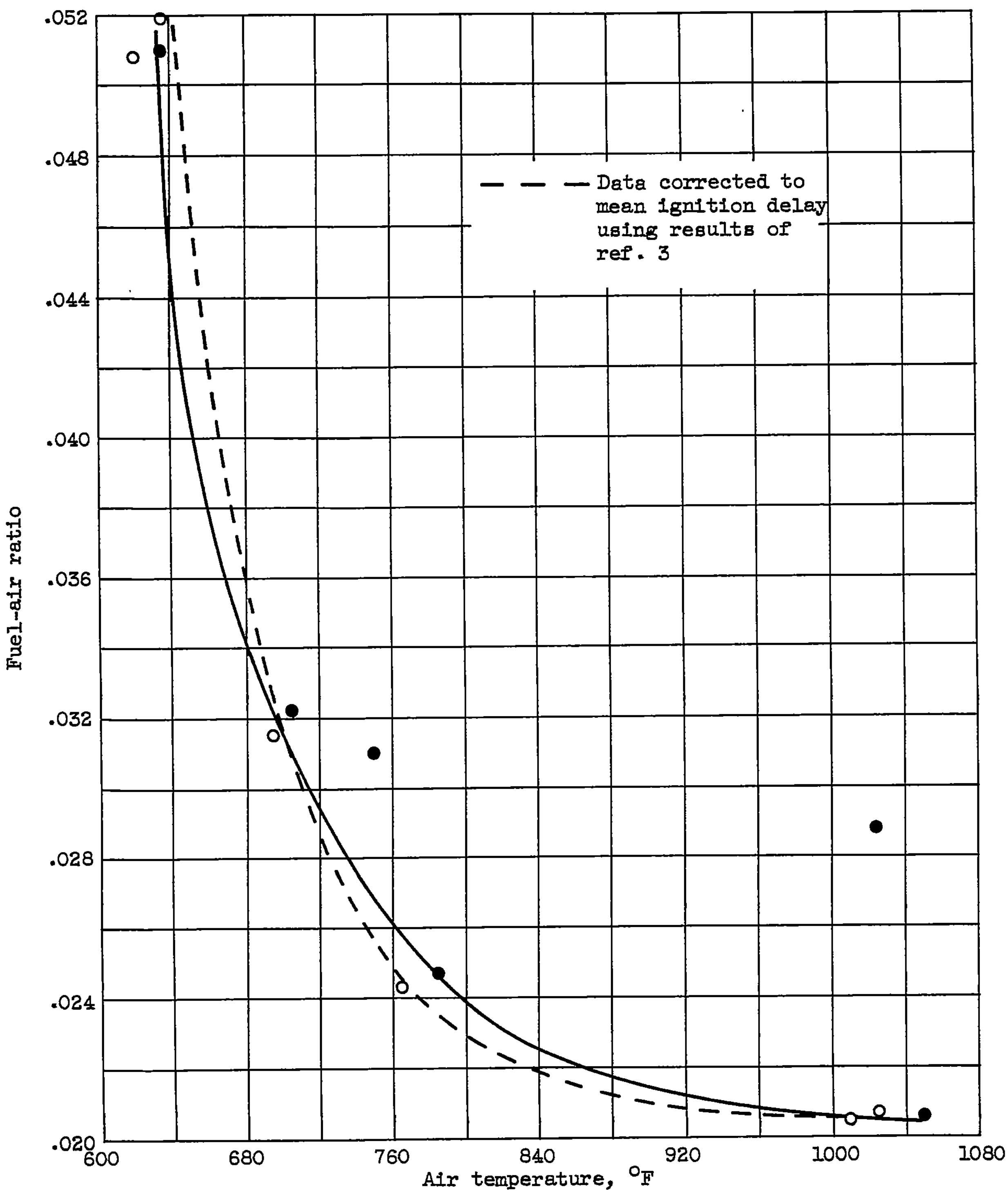

Figure 11. - Effect of fuel-air ratio on ignition temperature of amyl nitrate.

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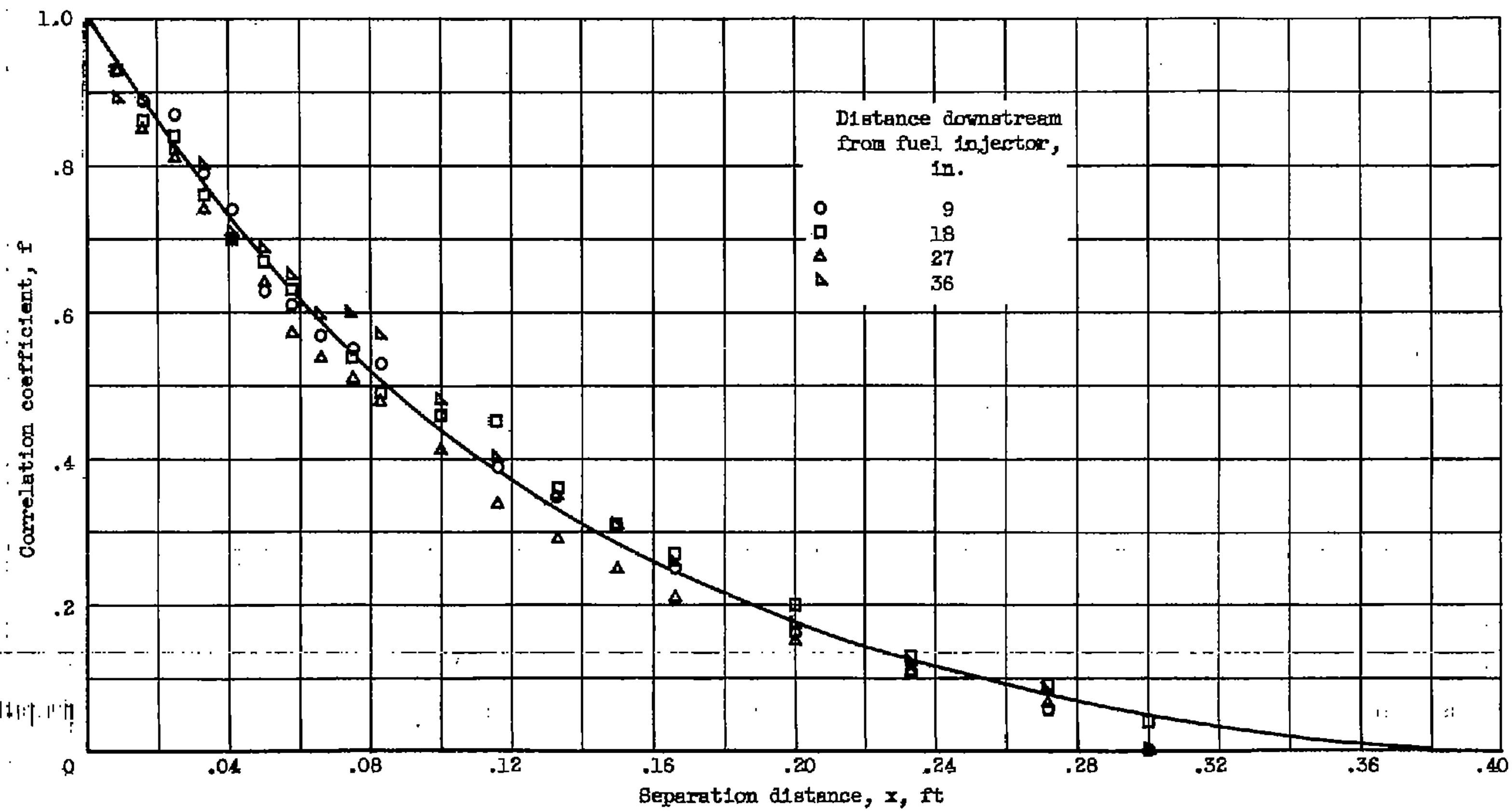

Figure 12. - Axial measurements of correlation coefficient f. Velocity, 250 feet per second; pressure, 29 inches of mercury absolute; air temperature, 200° F.

NACA - Langley Field, Va.